

THE RELATIONSHIP BETWEEN RADAR AREA-TIME INTEGRALS AND AREAL RAINFALL

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1. INTRODUCTION

Several investigators have reported the existence of a strong correlation between the area-time integral (ATI) based upon radar data and convective rainfall (e.g. Doneaud *et al.*, 1984; Lopez *et al.*, 1989; Short *et al.*, 1989; Johnson and Hjelmfelt, 1990). The approach used by most of these investigators considers the storm life history, with the reference frame centered on the storm. The radar data entered into the ATI calculation involved low-level scans with threshold reflectivity of 25 dBz to insure at least rough correspondence between the ATI and areas where precipitation reaches the ground. To relate the resulting ATI to a rain volume requires a simultaneously-collected "ground truth" rainfall data set. In most of the studies, a Z-R relationship based on either rain gage data or drop-size-distribution information is used to provide the ground truth. The relationship of rainfall to a satellite ATI based on infrared data has also been investigated (Johnson *et al.*, 1994).

The strong correlations reported ($r > 0.85$) indicate that the ATI relationships can be useful in studies at the regional and global scale. Atlas and Bell (1992) propose to use the technique in the Tropical Rainfall Measuring Mission (TRMM), a project designed to look at global-scale precipitation. For the hydrological community, however, the estimates of rainfall must be associated with specific areas on the ground. Thus, the question addressed here is the applicability of the ATI relationship to fixed target areas.

The data set selected for this study was acquired during the CCOPE project in the summer of 1981 by the Skywater radar (a C-band system with 1° beamwidth) at Miles City, Montana. This data set includes full volume scans recorded at 3-5 min intervals. The initial analysis effort has concentrated

on data collected during an 8.5-h period on 1 August 1981 (a day with activity over much of the radar surveillance area). Using the software package IRAS (Priegnitz and Hjelmfelt, 1993), CAPPI displays for 2.5 km altitude were generated and all ensuing analyses utilized these images.

The range considered was restricted from 20 to 156 km. A reflectivity threshold of 25 dBz was used in the calculation of the ATI's and a 10-dBz threshold was used in calculations of rain rate (R) based upon a Z-R relationship determined for the area (Smith *et al.*, 1975). The radar-estimated rain volume is based upon the rain rates multiplied by the respective echo areas and the time interval between scans. The ATI was computed as the sum of the area in each scan that equaled or exceeded 25-dBz reflectivity multiplied by the time interval between scans.

First, a "floating-target" analysis comparable to the earlier studies was conducted. Then a sample set of fixed areas was defined to investigate the applicability of the ATI concept in that framework.

2. FLOATING-TARGET ANALYSIS

A total of 54 radar echo clusters were found that had lifetimes from 2.8 - 492 min; the corresponding rain volumes ranged from 0.08 - 93,005 km² mm. The log-log regression of radar-estimated rainfall volume (RERV) calculated using the Z-R relationship on the ATI resulted in a correlation coefficient of 0.989, which is similar to values found in other studies. The slope of 1.21 is approximately 10% greater than those found in most of the previous studies, and the antilog of the intercept corresponds to a mean rainfall rate of 2.6 mm h⁻¹. The logarithmic standard error of estimate is 0.169 (about a factor 1.5).

Total rainfall received for the 8½ hour period in the total scan area of 75,200 km² was 115,730 km² mm, and the sum of the 54 ATI's was 14,382 km² h. Thus the rainfall coverage (above the 25-dBz threshold) was about 2.25% of the total possible space-time domain and the mean rainfall over the area was about 1.54 mm.

3. FIXED-TARGET ANALYSIS

A simple approach to fixed-area calculations was judged appropriate for this initial investigation. The surveillance circle was divided into four sectors, each being 18,800 km² in area. Figure 1 is a plot of the ATI's for the four-sector grid and the corresponding RERV values in a log-log format. The four points vary over more than two orders of magnitude and the relationship is quite linear, with a correlation of 0.997. The slope of the regression line is 1.12 with an intercept of 0.46 (whose antilog corresponds to 2.89 mm h⁻¹). The relationship for these fixed areas is quite similar to that found for the "floating-target" clusters. Thus, there appears to be a meaningful relationship between ATI and rainfall for fixed grid areas when the size of the grid element is large enough.

To investigate the effect of grid size on fixed-target ATI's, the initial grid was

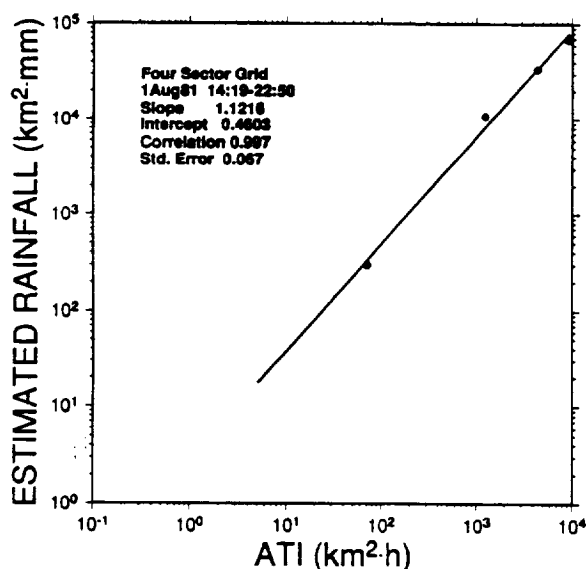


Figure 1. Log-log scatter plot of RERV vs. ATI calculated from the 8½ h histories of echoes in each sector of the 4-sector grid.

sub-divided into eight equal sectors, each of 9400 km². The same analysis procedure was applied to this grid with the results shown in Fig. 2. Only seven points are shown on the figure as the WSW sector included no pixels that exceeded the 25-dBz reflectivity during the 8½ hours. (There was a rain volume of 21 km² mm, based on reflectivities less than 25 but greater than 10 dBz; this corresponds to a mean rainfall over the sector of only 0.002 mm.) The scatter about the (dashed) regression line is increased, yet the fit is still good, with a correlation of 0.980. However, the slope changed significantly to 0.91 and the intercept is large (1.1524); its antilog corresponds to 14.2 mm h⁻¹, which is quite high relative to previous values.

Comparison of Fig. 2 with Fig. 1 indicates that only the smallest event, with rainfall slightly less than 200 km² mm (0.02 mm averaged over the sector), differs significantly from the trend of the rest. In this small event, only 10% of the rainfall was attributed to reflectivities ≥ 25 dBz. If one assumes that more than 50% of the rainfall must come from reflectivities ≥ 25 dBz before the smallest events are handled adequately by the ATI calculation using this threshold, this smallest event can also be deleted. Then the remaining six points yield a correlation coefficient of

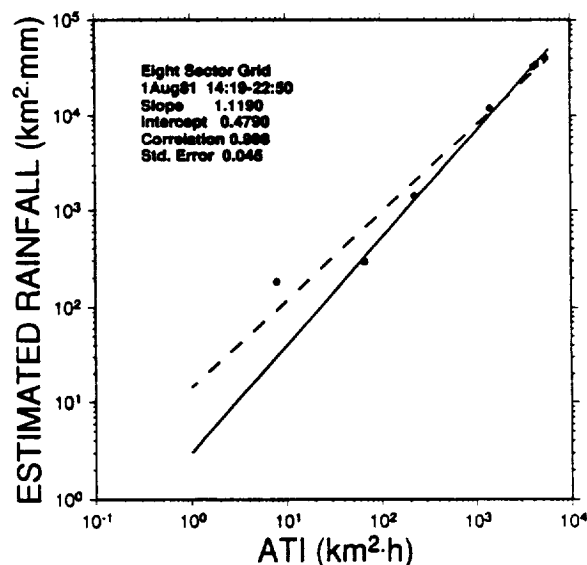


Figure 2. Same as Fig. 1, except for the 8-sector grid. Dashed line is regression for all 7 points; solid line (parameters shown) is that for all except the lowest point.

0.998 and a slope of 1.12 (solid line), which is quite similar to the four-sector result. The antilog of the intercept corresponds to 3.01 mm h^{-1} , which is also close to the previous values. Thus, it appears that the approach still is applicable to fixed areas of the order of $10,000 \text{ km}^2$ in size. However, caution must be exercised in treating extremely small events.

The grid was again subdivided by splitting each sector in half to create a 16-sector grid; each sector area is now 4700 km^2 . Again the analysis was repeated and the results are demonstrated in Fig. 3. Three of the sectors here never had a reflectivity that exceeded the 25-dBz threshold. The rain volumes calculated for these three sectors range from $0.6 - 4 \text{ km}^2 \text{ mm}$ (average rain less than 0.001 mm over the sector); they are not included in Fig. 3. The regression analysis yielded a correlation coefficient of 0.99, a slope of 0.90 (dashed line), and the antilog of the intercept corresponding to 15.4 mm h^{-1} . These values are quite similar to those obtained with Fig. 2, for much the same reasons. If small events with less than 50% of the rainfall coming from reflectivities $\geq 25 \text{ dBz}$ are eliminated from consideration, two points are removed. The regression of the remaining 11 points (solid line in Fig. 3) yields a correlation of 0.99, a slope of 1.06,

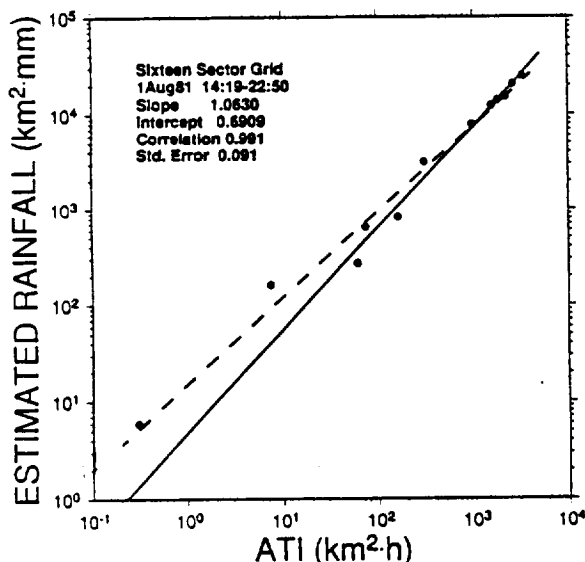


Figure 3. Same as Fig. 1, except for the 16-sector grid; dashed line is regression for all 13 points; solid line (parameters shown) for all except lowest two.

and the antilog of the intercept corresponding to 4.91 mm h^{-1} . Therefore, it again appears that application of the ATI approach to fixed grid elements approximately $5,000 \text{ km}^2$ in size yields acceptable results, with the caveat that all sectors must have more than 50% of the rain coming from reflectivities $\geq 25 \text{ dBz}$.

4. DISCUSSION AND CONCLUSIONS

Comparison of the results of the regressions demonstrated by Figs. 1, 2, and 3 indicates that significant differences exist. However, most of the substantial differences are at the low end of the scales, and after eliminating from the analysis cases with $> 50\%$ of the rainfall from reflectivities $< 25 \text{ dBz}$, the regressions become more nearly coincident. The slopes of the regressions then vary only from 1.12 for the 4-sector grid to 1.06 for the 16-sector grid, while the antilog of the intercept ranges from $2.89 - 4.91 \text{ mm h}^{-1}$. Therefore it appears that the ATI remains well correlated with rainfall for fixed areas down to about $5,000 \text{ km}^2$, with the provision that events with small rain amounts mostly due to echoes $< 25 \text{ dBz}$ not be allowed to influence the regression. Of course, this means that good rain estimates cannot then be obtained for such events, but that is a less serious problem than making errors at higher rain amounts.

In using ATI observations to estimate rain volumes, a calibration such as given in Sec. 2 or Sec. 3 is required. However, use of the relationships for verification here would not provide an independent test. To obtain an independent verification, a separate calibration that was determined from the North Dakota Cloud Modification Project radar data collected in 1981 at Bowman, ND (Doneaud *et al.*, 1984) was applied. The NDCMP radar set at Bowman and the Skywater set at Miles City differed in beamwidth (2° , 1°) and range gate spacing (1 km , $\frac{1}{2} \text{ km}$). Cloud types and precipitation mechanisms were similar as the two sites are separated by only some 200 km . The analysis of the NDCMP data followed the Lagrangian method, and the relationship was found to be $\text{RERV} = 3.07 (\text{ATI})^{1.08}$.

Application of this relationship to the CCOPE ATI values for all the fixed grids yields a set of rain volumes that can be directly compared to the RERV for the corresponding

cases. This comparison is summarized in Fig. 4; the solid line is the one-one line where all points would lie if the test were perfect. Most of the points lie slightly above this line, indicating that the rain volume is slightly underestimated by using the ATI with this independent calibration. The three points far to the left side represent the three sectors that received very light rainfall from reflectivities mainly below the 25-dBz ATI threshold. This demonstrates that an independently-developed calibration can be applied with fixed-target ATI's to obtain reasonable rainfall estimates.

The ATI approach yields good correlations with estimated rainfall when applied to fixed targets of 5,000 km² area or greater. While only regular sectors were tested here, the shape of the grid could presumably be chosen to conform to the boundaries of specific watersheds. The method would then provide an estimate of rainfall received by each watershed. No lower limiting value for grid sector size has been found in this study; further reductions in the uniform grid will be examined. These preliminary results do indicate that, as the sector area is reduced, the opportunity increases for any one sector to receive more than 50% of its rainfall from regions with

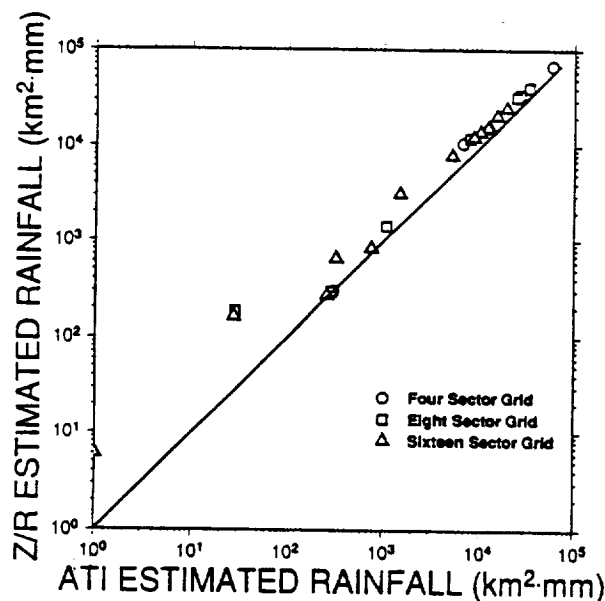


Figure 4. Log-log scatter plot of RERV for the various sectors vs. the rain volume estimated using a rain-volume/ATI correlation developed from 1981 NDCMP data. The solid line is the idealized one-one comparison.

reflectivities < 25 dBz. Inclusion of these sectors may lead to less satisfactory results.

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